ELECTRIC POWER FOR STREET RAILWAYS

BY

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THESIS

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I HEREBY RECOMMEND THAT THE THESIS PREPARED BY

John Thomas Donahoe

ENTITLED Electric Power for Street Railways

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

PROFESSIONAL DEGREE OF Electrical Engineer.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Note: Figures 3,4,5 and 6 are copies, except for some minor changes, of working drawings for sub-stations of the Chicago Surface Lines.

ELECTRIC POWER FOR STREET RAILWAYS

I. GENERAL DISCUSSION

When electric power was first used to propel street cars, the power was invariably supplied by a steam generating station which usually fed a large area. In the smaller cities one station would supply the entire system; while in the larger cities several plants would be built.

The steam plants generated direct current at 600 volts and all distribution was at that potential. The economies of operating a large generating station over a small one were balanced against the greater line loss in the 600 volt feeders. It soon became apparent, however, that transmitting a large amount of power at 600 volts over a large area entailed a considerable loss. It was also discovered that a considerable saving in boiler capacity and apparatus in general could be effected if the railway and other light and power loads were combined and supplied from a common source. These facts led to the development of the sub-station supplied from a central generating station with alternating current at 9000, 12000 or 22,000 volts.

The sub-stations receive the alternating current and convert it to direct current at 600 volts for railway distribution. In many of the larger cities the railway companies have turned over to the electric light and power company the entire job of supplying them with direct current power. The advantage, however, of having the direct current feeders in the hands of railway employees is so great that many of the larger companies are operating the sub-stations and buying the alternating current from the light and power company.

It is the purpose here to discuss the location, design, and testing of railway sub-stations and take up the distribution of 600 volt direct current from the sub-station to the car. The question of electrolysis and the various systems of electrolysis mitigation will be thoroughly discussed.

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II. LOCATION OF THE SUB-STATION

The location of the sub-station is one of the most important questions in connection with the supply of electric power for street railways. A poorly located sub-station will make a very inefficient system. The location of a sub-station depends on the following factors:

1. Location of the Center of Load.
2. Location of Conduit Lines.
3. Property Values.
4. Future Growth of the System.
5. Car House Load.

The first factor can be determined with mathematical exactness. By means of the spot map shown in figure 1, the number of cars per section is found for each street. Extensive tests should be made to determine the amount of current taken by the average car. When the current per car and the number of cars are found, the ampere load on each section is calculated (see figure 2). The center of load is found in the same way as the center of gravity by using the principle of moments. A line of reference is chosen and the ampere load on each section is multiplied by its distance from the reference line, the load on each section being considered concentrated at the center of the section. These moments are added algebraically and the distance of the center of load from the reference line found by dividing the sum of the moments by the total load on the sections. The center of load lies on a line drawn parallel to and at the found distance from the reference line.

This is repeated using another reference line at right angles to the first. The intersection of the lines drawn parallel to the reference lines is the center of load.

The second factor, while not as important as the first, should be given some consideration. The location of conduit lines may make it desirable to place the sub-station at a point which is not at the center of load. Where high and low tension lines are allowed to be placed overhead, this point will not have to be considered. The cost of building a pole line is so small, in comparison to the benefit derived from having the station at the exact center of load, that it need not be given much weight. However, where all high and low tension lines must be placed underground, a location near an existing conduit line will have an immense advantage over a location at some distance from the conduit lines.

The station should be placed where the property can be purchased at a reasonable price. It is well, however, to take into consideration the type of buildings on the street on which the station is to be placed. If one street has a number of fine residences, while another is a business street, it may be well to place the station on the business street. The reason for this is that a cheaper building can be built, as a rule, on the business street and there is less objection from adjacent property owners. If it

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FIGURE 1

SPOT MAP

SHOWING CAR DISTRIBUTION
IN

39TH ST. DISTRICT

DURING RUSH HOUR

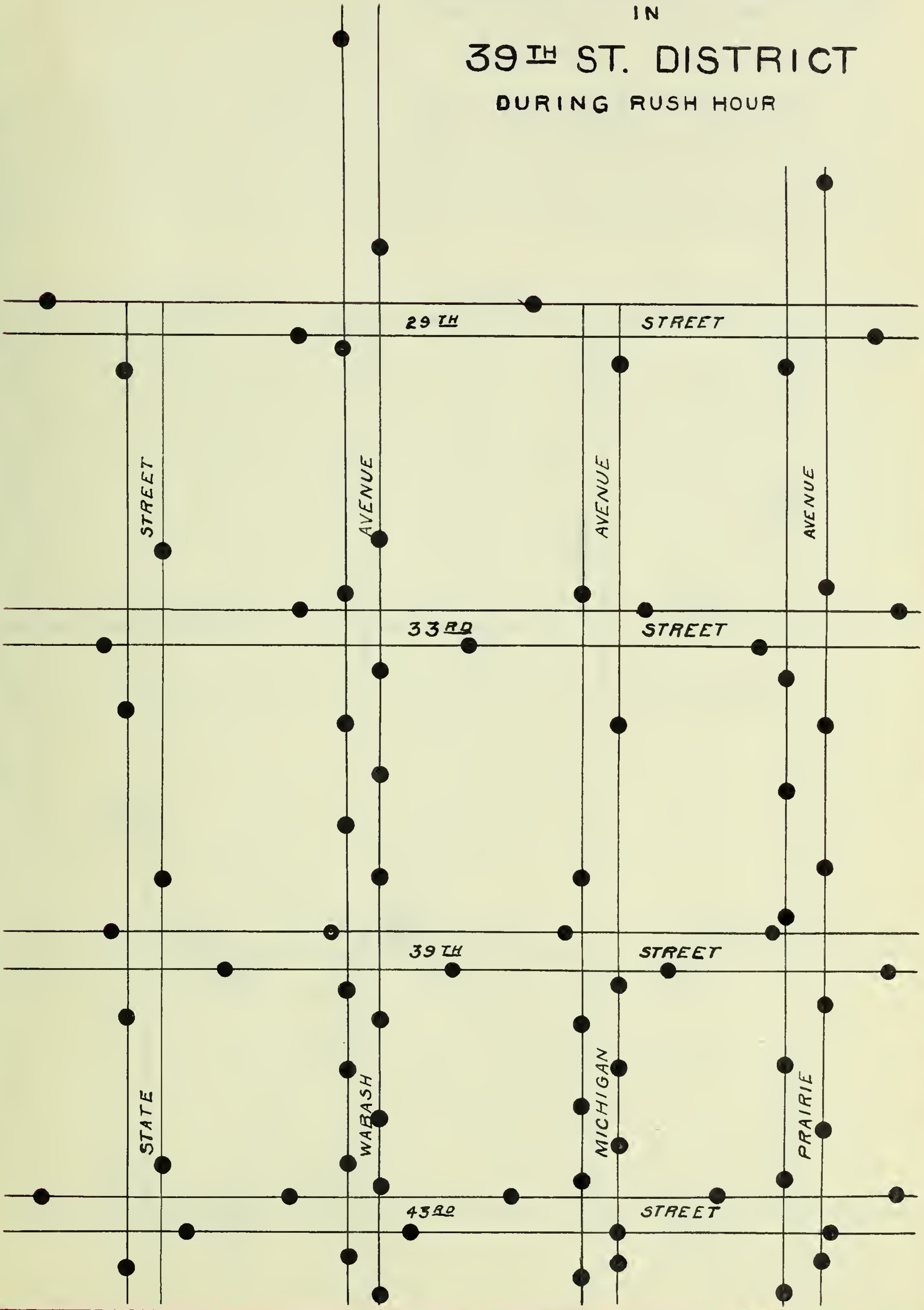
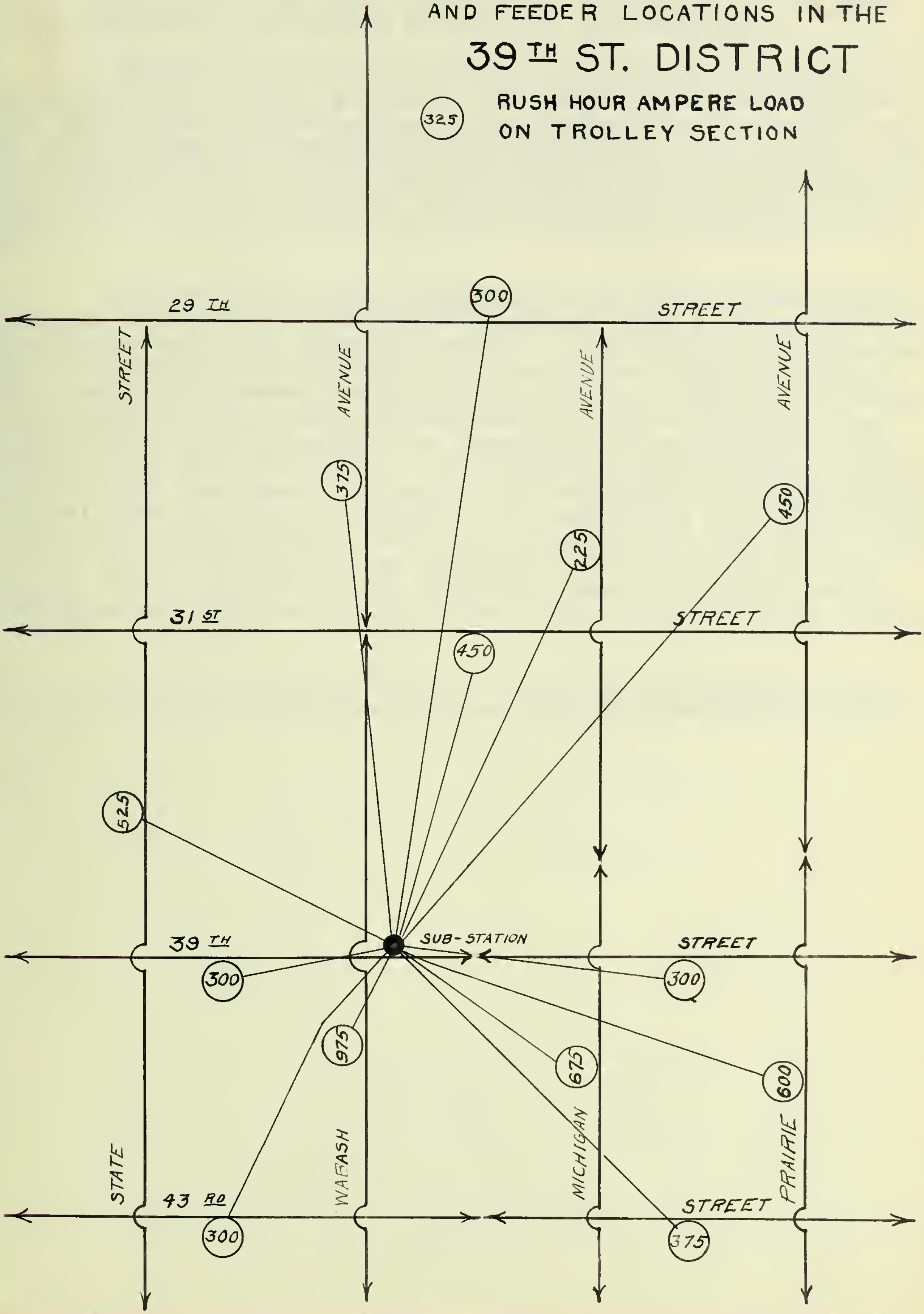


FIGURE 2

SPIDER DIAGRAM

SHOWING TROLLEY SECTIONS AND FEEDER LOCATIONS IN THE

39 TH ST. DISTRICT



is found desirable to place the station on a residential street, the building should be of such design as to harmonize with the other buildings in the same block. This need not greatly increase the cost of the building as some very attractive designs can be made without materially increasing the cost of construction.

The sub-station should not be located without taking into consideration the future growth of the system. The direction in which the system is growing should be determined and a careful study made with a view to forecasting load conditions in the future. If it is found from this study that the growth is in a given direction and that in the near future an additional sub-station will be required, it is well to figure on this in locating the present sub-station.

Another point which should be given considerable weight is the car house load. This is an important factor especially where the cars are heated by electric heaters. The heat is turned on an hour or two before the cars leave the car house. This places a load of several thousand amperes on the large car houses and makes it desirable to have a sub-station near at hand to furnish this power with as little line loss as possible. Some companies place a sub-station at each car house. The advantages of locating a sub-station at the car house are many. The car house is furnished power with a minimum line loss. Usually the company has available vacant property near the car house or there is room in the car house itself to place the sub-station. The car house is usually placed where there is little objection from property owners, and there would probably be no objection to the sub-station if placed in or near the car house.

All these factors should be thoroughly studied and from this study the most desirable location for the sub-station chosen.

III. DESIGN OF THE SUB-STATION

Having fixed the location, the next step is the design of the sub-station. As stated above, the building should harmonize with the adjacent buildings. If on a residential street, it is well to secure enough ground to provide for a lawn around the building.

The building should be large enough to accommodate the apparatus without crowding. Many lives have been lost and much equipment damaged by having the apparatus crowded into a small station. Some companies have gone from one extreme to the other on this point - the first stations being crowded and the latter stations having room to spare.

The first step in the design of the station is to decide what apparatus will be required. On this point there has been some difference of opinion. Figures 3 and 4 show the connections for a sub-station of one of the large railway companies. In this station an immense amount of unnecessary apparatus was installed. There are recording wattmeters, recording voltmeters, synchronism indicators, transfer oil switches, totalizing ammeters and direct current starting switches. All of the above mentioned apparatus has been found to be of very little use. There is still some question as to whether a crane is necessary. Below is listed the apparatus which should go to make up each power unit.

Line oil switch. (Either motor-operated or solenoid-operated)
Machine oil switch. (" " " " " ")
One three-phase or three single phase transformers.
One reactance.
A.C. starting switches giving 1/3, 2/3 and full voltage on the alternating-current side of the converter.
A rotary converter or motor-generator set.
A direct-current machine switch (single-throw).
Three alternating-current single phase induction watt-hour meters with necessary transformers.
Line and machine alternating-current ammeters.
Line and machine relays.
Power factor indicator.
Alternating-current voltmeter.
Direct-current voltmeter.
Direct-current watt-hour meter.
Direct-current ammeter.
Circuit breaker.

In addition to the above mentioned apparatus, the station should have a battery for operating the oil switches and for emergency lights. The diagram of connections of this apparatus is shown in figure 5. Synchronous converters are being used much more than motor-generator sets. The converters are more efficient, take up less room, can be started without synchronizing and cost less than motor-generator sets. If air cooled transformers are used, a blower must be furnished for each transformer. The station should also be furnished with a pump and motor to prevent flooding of the basement.

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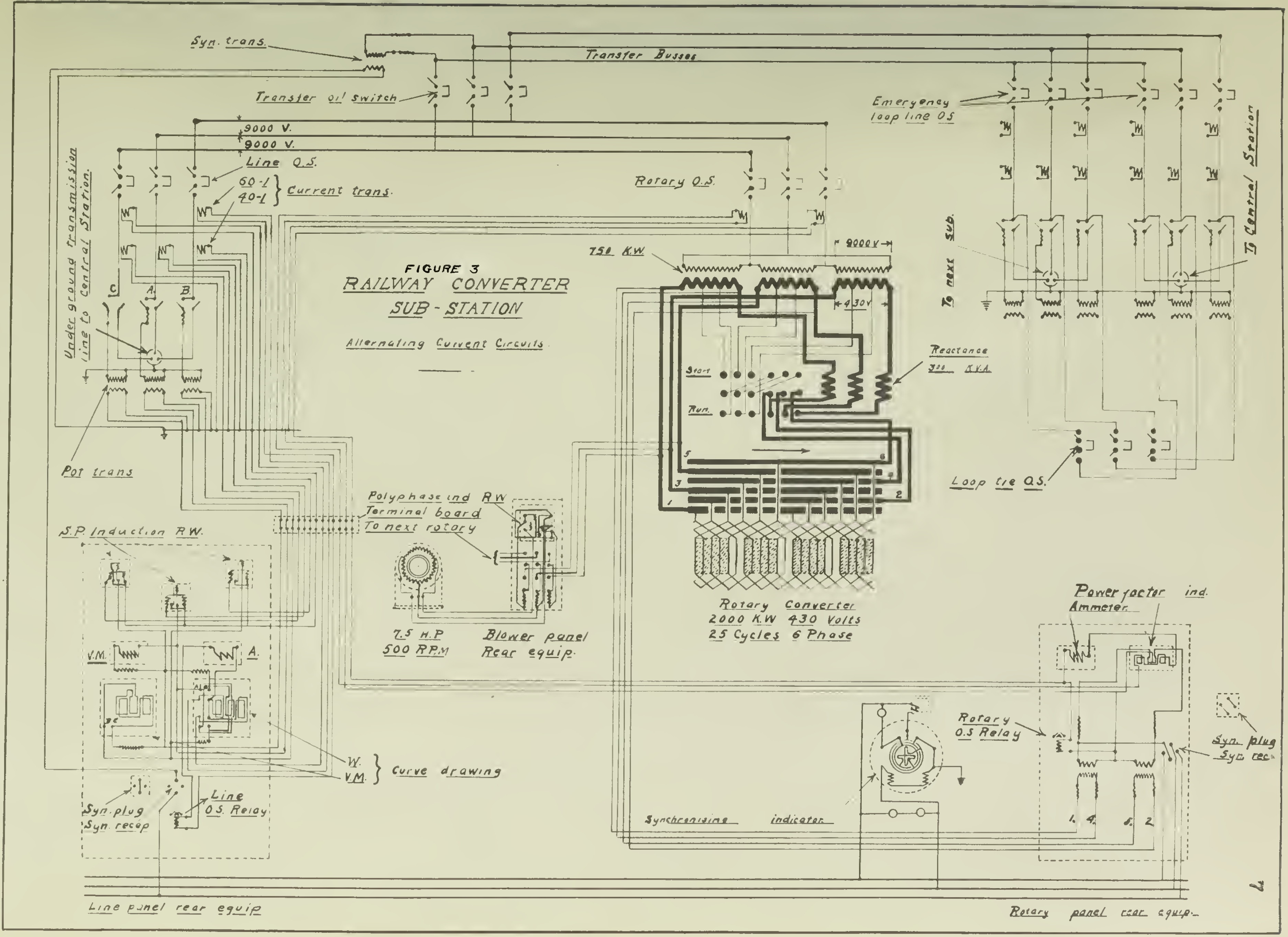


FIGURE 3
RAILWAY CONVERTER
SUB-STATION

Alternating Current Circuits

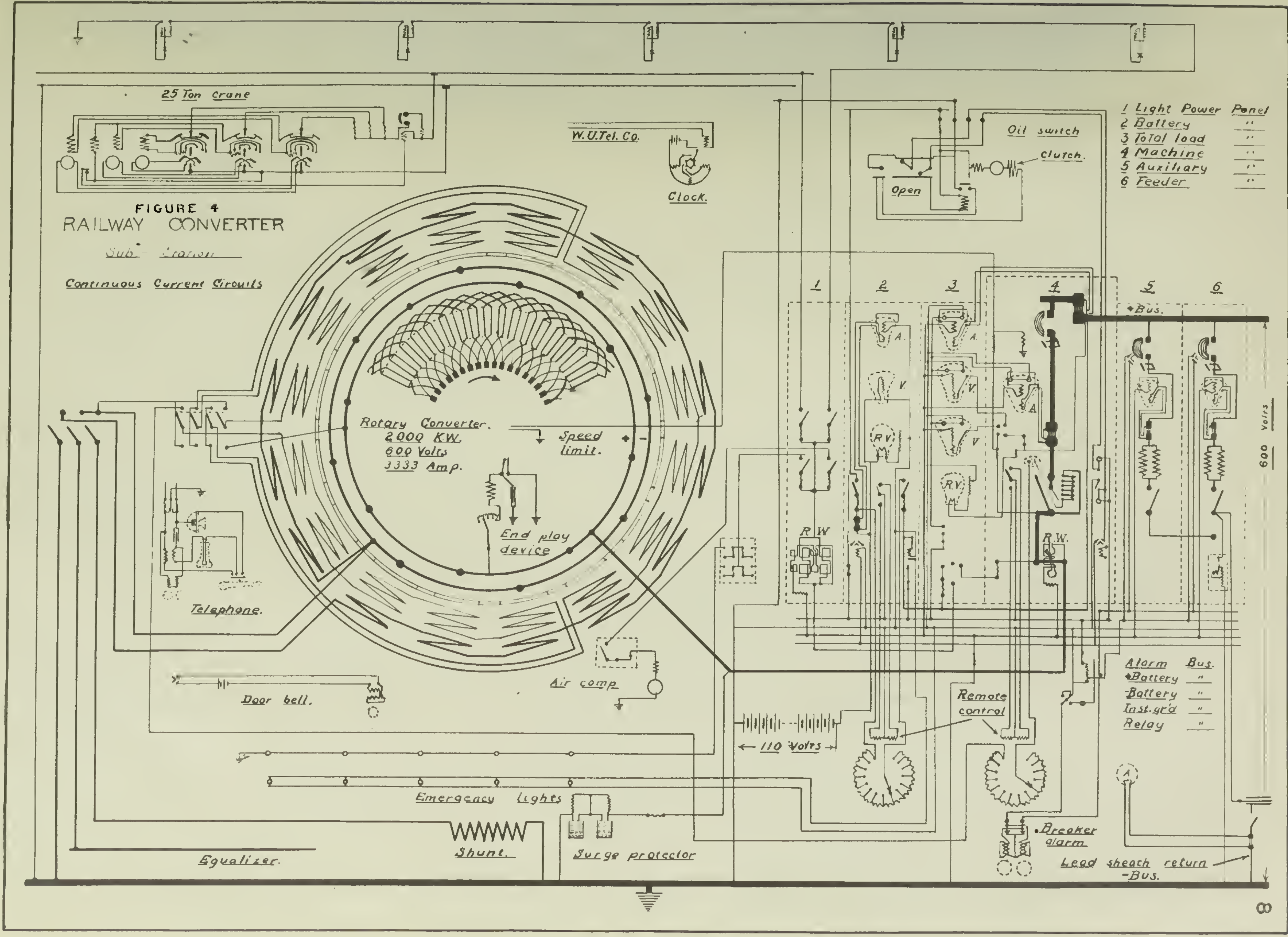


FIGURE 4
RAILWAY CONVERTER
Sub-Station
Continuous Current Circuits
25 Ton crane
W.U.Tel. Co.
Clock.
Oil switch
clutch.
Open
1 Light Power Panel
2 Battery "
3 Total load "
4 Machine "
5 Auxiliary "
6 Feeder "
+Bus.
600 Volts
Rotary Converter.
2000 K.W.
600 Volts
3333 Amp.
Speed limit.
End play device
Telephone.
Door bell.
Air comp.
R.W.
A.
V.
R.V.
Alarm Bus.
+Battery "
-Battery "
Inst. gr'd "
Relay "
Remote control
← 110 Volts →
Emergency Lights
Shunt.
Surge protector
Equalizer.
Breaker alarm
Lead sheath return
-Bus.
8

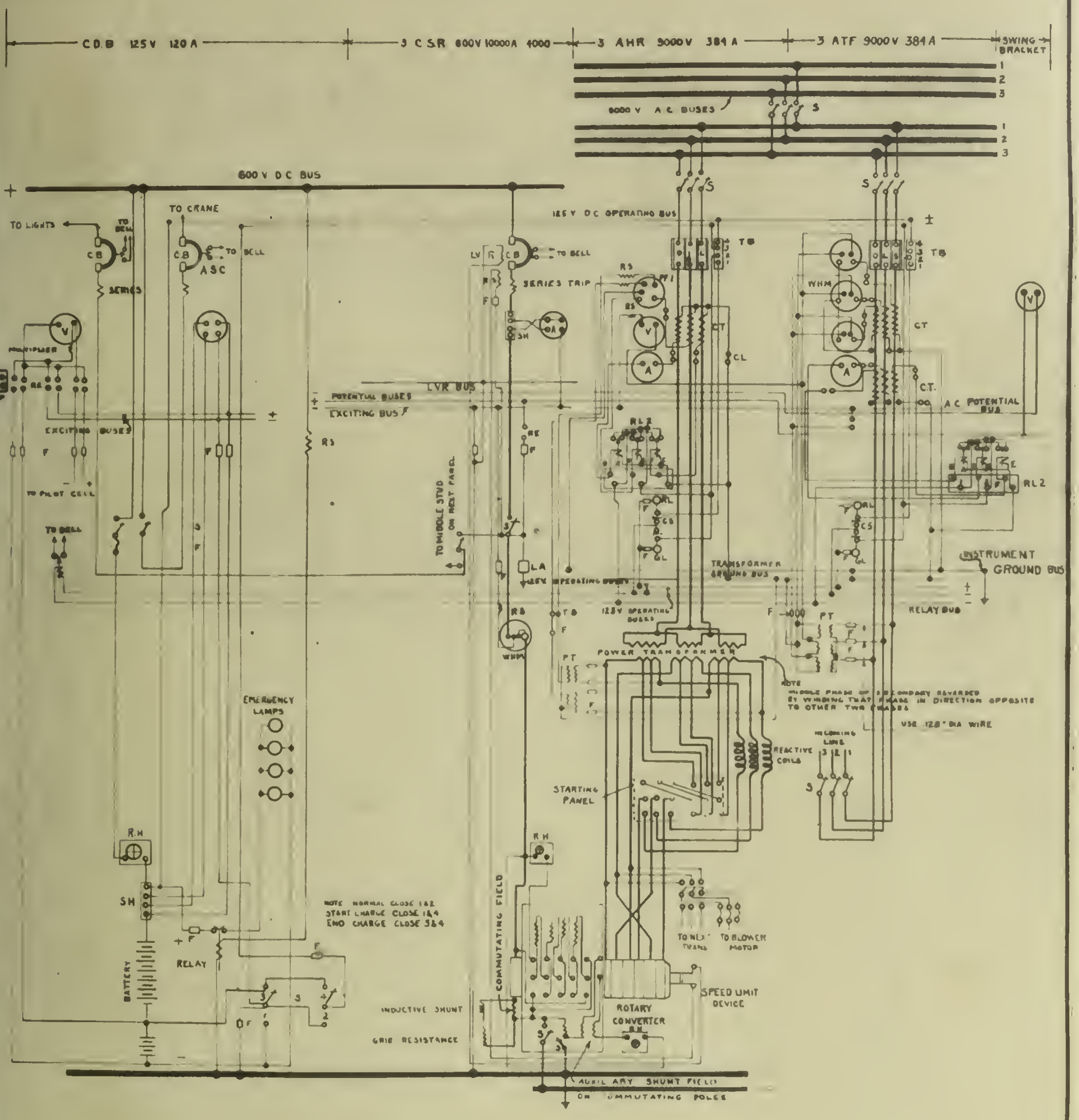


FIGURE 5

SWITCHBOARD WIRING

BACK VIEW

A DIAGRAM OF CONNECTIONS

FOR A STREET RAILWAY SUB-STATION

A	AMMETER
ASC	AUXILIARY SWITCH CIRCUIT CLOSING
ASO	" " " OPENING
C.B.	CIRCUIT BREAKER
C.L.	CALIBRATING LINK
C.S.	CONTROLLING SWITCH O S
C.T.	CURRENT TRANSFORMER
C.D.A	CURVE DRAWING AMMETER
C.D.V	" " VOLTMETER
C.D.W	" " WATTMETER
CH.C	CHOKE COIL
D.R	DISCHARGE RESISTANCE
F	FUSE
F.I	FREQUENCY INDICATOR
G.D	GROUND DETECTOR
G.L	GREEN LAMP
G.S	GOVERNOR CONTROL SWITCH O S
I.R	REACTANCE
L	LAMP
L.A	LIGHTNING ARRESTER
L.V.R	LOW VOLTAGE RELEASE
P	POTENTIAL PLUG
P.F.I	POWER FACTOR INDICATOR
I.W.	INDICATING WATTMETER
P.P.B	PUSH AND PULL BUTTON
P.T	POTENTIAL TRANSFORMER
R	RHEOSTAT
RE	RECEPTACLE
REG	REGULATOR
RL	RED LAMP
R.L.1	INSTANTANEOUS RELAY O S
R.L.2	INVERSE TIME LIMIT RELAY O S
R.L.3	DEFINITE " " " O S
R.L.4	DIFFERENTIAL RELAY O S
R.L.5	D C REVERSE CURRENT RELAY O S
R.P	SYNCHRONIZING PLUG RUNNING
R.S	RESISTANCE
S	SWITCH
SH	SHUNT
S.I	SYNCHRONISM INDICATOR
S.P	SYNCHRONIZING PLUG STARTING
T.B	TERMINAL BOARD
T.P.B	TWIN PULL BUTTON
V	VOLTMETER
W.C.I	WATTLESS COMPONENT INDICATOR
W.H.M	WATT-HOUR METER

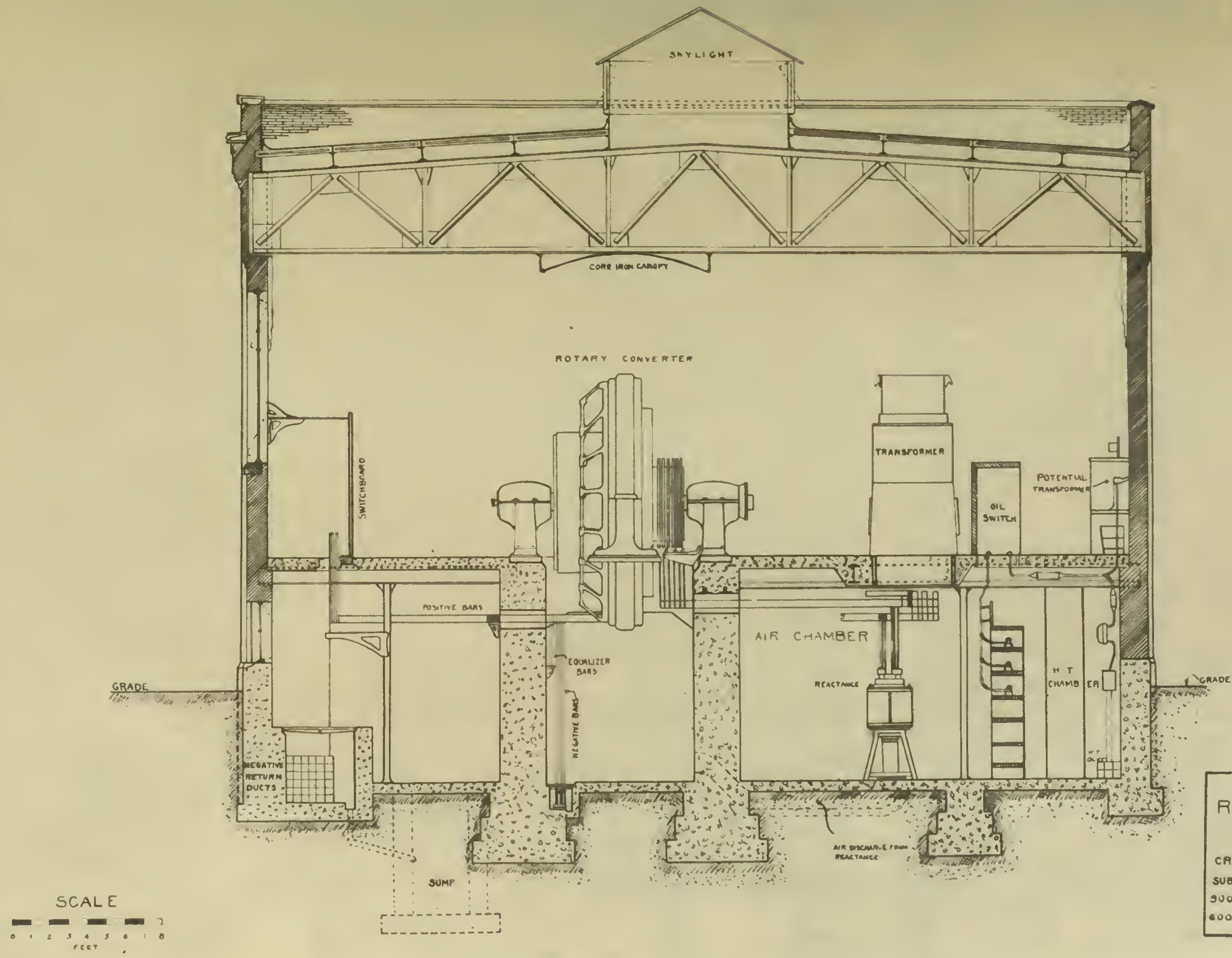


FIGURE 6.
ROTARY CONVERTER
SUB-STATION

CROSS SECTION OF TYPICAL LARGE SUB-STATION (1919) 8,000 KILOWATT 9000-VOLTS ALTERNATING CURRENT, 600-VOLTS DIRECT CURRENT

The arrangement of the apparatus in the station is fairly well standardized. Figure 6 shows a cross section of a modern sub-station. The alternating-current lines enter the station at one side and go to oil switches. Close to the oil switches are the power transformers and below the power transformers in the basement air chamber is the reactance. The converter is placed almost in the center of the station with about ten feet of floor space around it. Near the wall opposite the oil switches is the switchboard. Below the switchboard are the direct-current cable racks. No crane is shown and the ceiling is rather low. On account of the low ceiling, a skylight is installed to give added light and ventilation. The battery is placed in a special room in the basement. This room is provided with concrete shelves for the cells. The blowers are placed in the basement near the front windows. This station is designed for two 4,000 Kw. converter units. The building is approximately 50 feet wide by 60 feet long and 30 feet high. The exterior walls are of vitrified brick trimmed with cut stone. The interior walls are of pressed brick. The floors are of reinforced concrete. The doors on the air chamber and the battery room are constructed of metal, as are all the window frames and sashes.

Considering the capacity of the station, the building is about as small as could be built without crowding the apparatus. The apparatus can be arranged in many different ways but unless there is a saving of floor space or copper no advantage is gained by changing the standard design. In some instances a building occupies the ground to be used for the sub-station. It may be possible to remodel this building and make a very good sub-station. Before attempting to remodel a building, a very careful estimate of the cost should be made. The sub-station described above can be built for about $20,000, and if there is not a considerable saving effected by using the remodeled building, it will probably be advisable to build an entirely new station.

IV. TESTING OF SUB-STATION APPARATUS

In order to insure continued operation of the sub-station, the apparatus should be tested at regular intervals. Figure 10 is a chart showing the schedule of tests for a given sub-station.

1. Direct Current Watt-hour Meters.

Direct-current watt-hour meters should be checked once a month. The method used is illustrated in figure 7. A shunt is inserted in place of the machine switch. The current coil of a standard watt-hour meter is connected across the shunt, and the potential coil is connected in parallel with the machine voltmeter. The machine watt-hour meter is checked against the standard watt-hour meter.

If a standard watt-hour meter is not available, the watt-hour meter can be checked by placing a millivoltmeter across the shunt and a standard voltmeter in parallel with the machine voltmeter. Ten or twenty revolutions of the meter armature are timed with a stop watch. At the same time the millivoltmeter and voltmeter are read and the readings averaged. By means of the following formula, the per cent accuracy of the meter is determined.

$$\text{Standard watt seconds } (Ws) = \text{Volts} \times \frac{\text{Millivolts}}{\text{Rest. of shunt}} \times \text{seconds.}$$

$$\text{Meter watt seconds } (Wm) = \text{Armature revolutions} \times \text{Disc constant.}$$

$$\text{Per cent accuracy} = 100 + \frac{Wm - Ws}{Ws}$$

Below the armature of the meter, and attached to it, is an aluminum disc which rotates between a set of damping magnets. By moving the magnets away from the center of rotation of the disc, the meter can be slowed down; and by moving the magnets towards the center of rotation the meter can be speeded up. In this way any desired adjustment can be had.

2. Direct Current Ammeters.

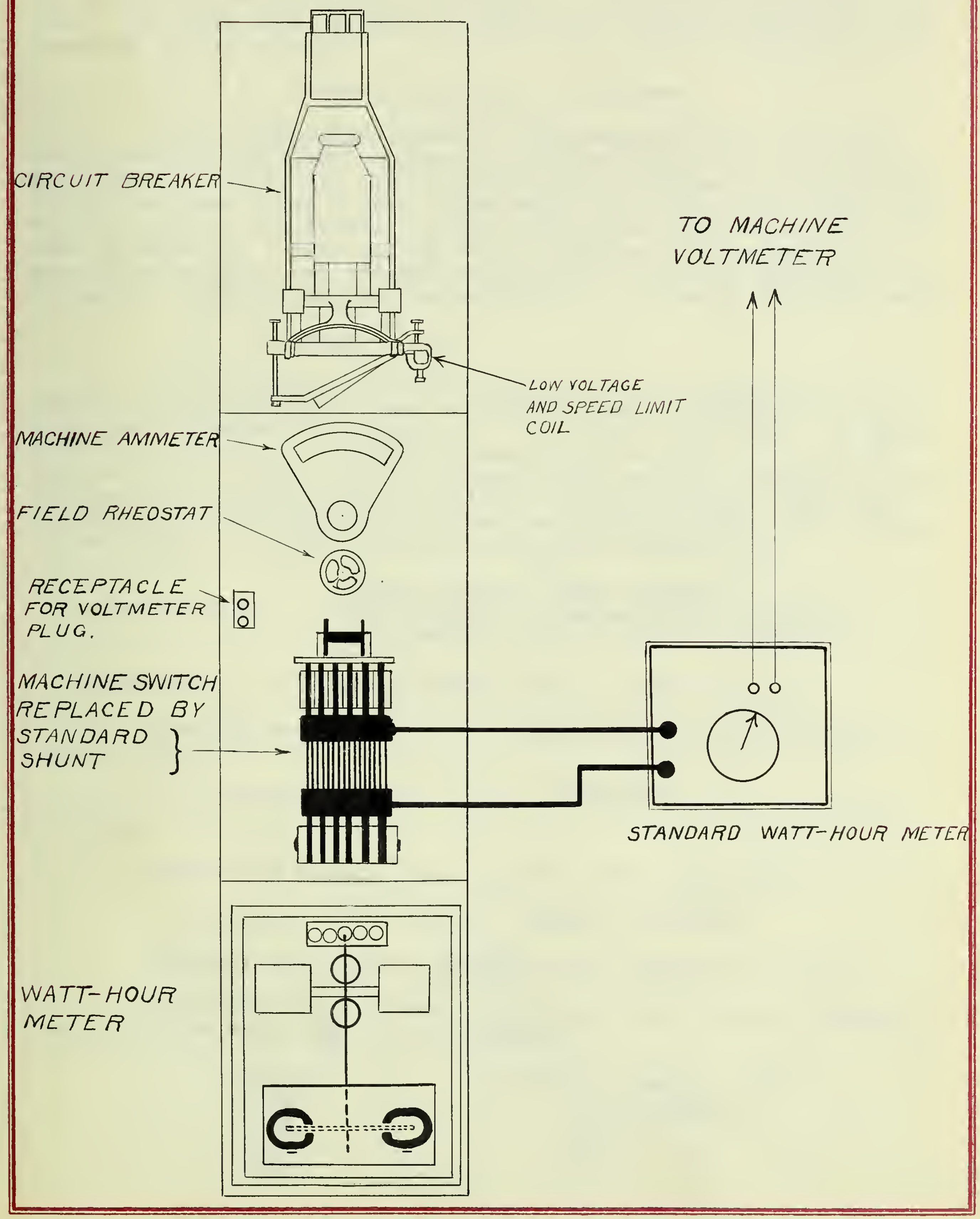
By connecting a millivoltmeter across the shunt shown in figure 7, the machine ammeter can be checked. The voltage drop over the shunt divided by the resistance of the shunt gives the current flowing. The readings of the ammeter and millivoltmeter are averaged for a period of three minutes. The average ammeter reading should equal the average millivoltmeter reading divided by the resistance of the shunt. The ammeter is adjusted by means of a resistance wire which is in series with the armature of the meter.

3. Direct Current Voltmeters.

In order to maintain a uniform voltage on the trolley,

FIGURE 7

CONNECTIONS FOR TESTING
D.C. WATT-HOUR METER



the direct current voltmeters must be accurate. Both line and machine voltmeters should be calibrated once every five or six weeks. The method of doing this is to insert a standard voltmeter in parallel with the meter to be tested. Simultaneous readings are taken on both meters and the accuracy determined for the meter under test. The adjustment is made by means of a counter weight on the armature of the meter.

4. Alternating Current Voltmeter.

The alternating current voltmeters are not of as much importance as the direct current voltmeters. However, they should be fairly accurate. In order to keep them accurate, they should be checked at least once a year. The method of doing this is the same as that used on the direct current voltmeters. The adjustment is made by means of a hair spring on the armature of the meter. In direct and alternating current voltmeters, a further adjustment can be had by changing the resistance which is in series with the meter.

5. Relays.

The adjustment of the relays should be carefully studied. The point that should be kept in mind is that the purpose of the relay is to protect the apparatus. In order to do this, the apparatus should never be allowed to take more load than it is guaranteed to stand. Most railway apparatus will stand a hundred per cent overload for a short period of time. The minimum setting of the relay should not exceed one hundred per cent overload. The following settings have given very good results wherever used:

Machine Relay --	Minimum setting 100% overload. Time setting - 4 seconds 125% overload. Instantaneous setting 350% overload.
Line Relay -----	Instantaneous setting 500% overload.

The current taken by the relay with different loads is found as follows:

A 2,000 Kw. Converter takes $\frac{2,000,000}{3}$ or 666,666 watts per phase.

Watts per phase = volts times current per phase.

$$666,666 = 5,200 \times \text{amperes per phase.}$$

$$\text{Amperes per phase} = \frac{666,666}{5,200} = 128 \text{ amperes per phase.}$$

With a 60 to 1 current transformer, the current flowing through the relay is $\frac{128}{60}$ or 2.13 amperes.

Overload	Current through relay
100%	4.26 amperes
125%	4.80 "
350%	9.60 "
500%	12.80 "

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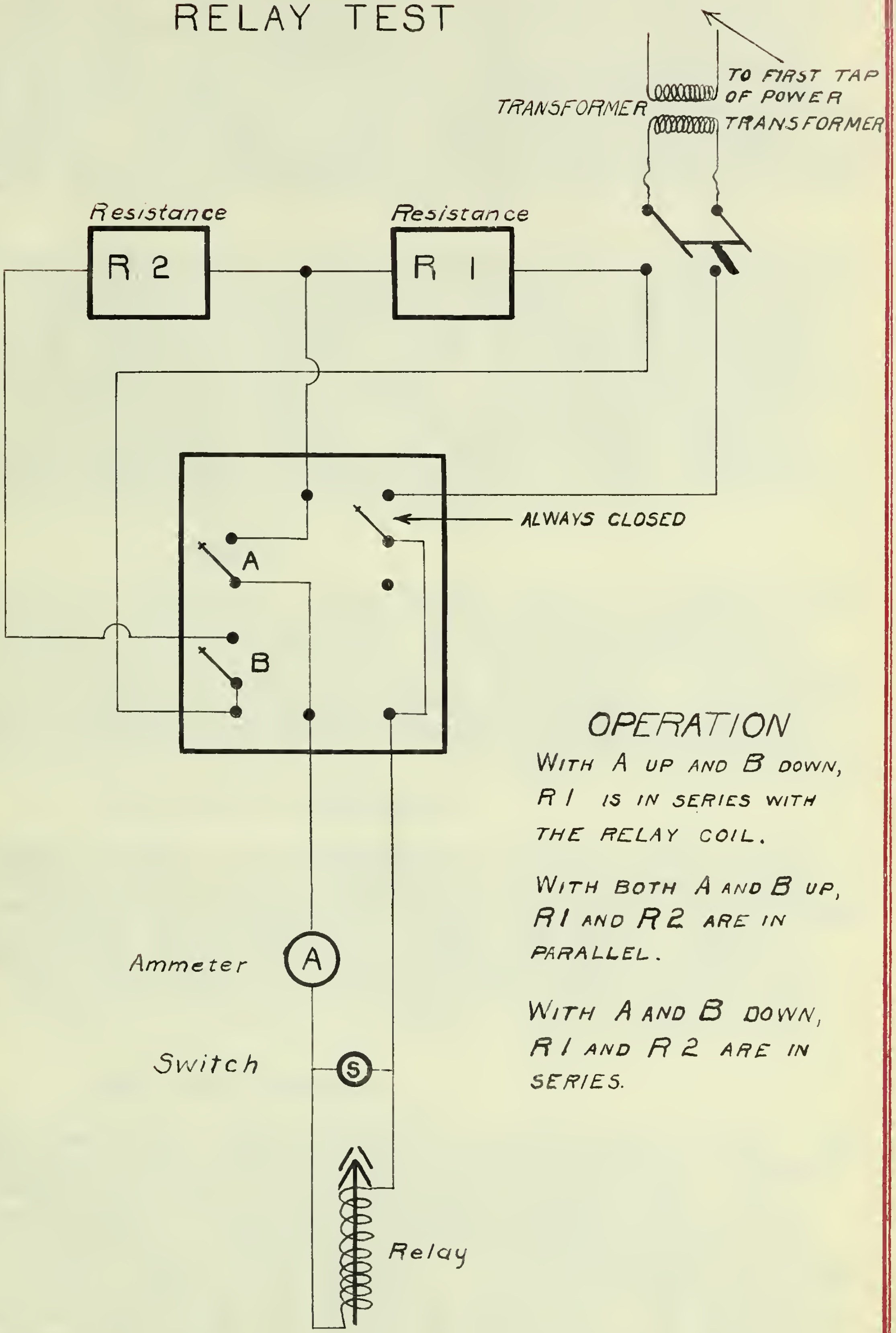
FIGURE 8

RELAY TEST



OPERATION

WITH A UP AND B DOWN, R 1 IS IN SERIES WITH THE RELAY COIL.

WITH BOTH A AND B UP, R 1 AND R 2 ARE IN PARALLEL.

WITH A AND B DOWN, R 1 AND R 2 ARE IN SERIES.

J.T.D.

Figure 8 shows the connections for calibrating relays. A one to one current transformer is placed across the first step of the power transformer. The purpose of the current transformer is to avoid grounding the power transformer in case any of the testing leads become grounded. By changing the variable resistances R 1 and R 2, any desired current can be sent through the relay. The relay is disconnected from its current transformer and connected as shown in figure 8. The relay is first adjusted for the minimum load. The air valve is removed and, by means of an adjustment screw on the plunger, the relay is adjusted to trip at 100 per cent overload.

In the air valve is a spring which controls the instantaneous valve. This spring can be adjusted so that if a sudden pressure comes on the valve it will release instantly. This spring is adjusted for 350 per cent overload. After the minimum and instantaneous settings have been made, the relay is adjusted to operate at a definite time with a given overload. This is done by means of a needle valve which allows the air, from the bellows which is attached to the plunger, to escape in a definite time. When the time setting has been made the other settings are again checked to see that the adjustment has not been changed.

6. A. C. Ammeters.

While the relays are being checked the A. C. ammeters can be easily checked. With the apparatus as shown in figure 8, all that is necessary is to disconnect the ammeter from its current transformer and connect it as the relay is in figure 8. By adjusting R 1 and R 2 any desired current can be sent through the ammeter which is checked against the standard ammeter shown in figure 8. The adjustment is secured by means of a hair spring on the armature.

7. Power Factor Indicators.

Figure 9 shows the connections for testing power factor indicators. The indicator is disconnected from its potential and current transformers and connected as shown in figure 9. With lamp bank 1 out the meter should register a power factor of .866 lag. With lamp bank 2 out the meter should register a power factor of .866 lead. With lamp banks 1, 2, and 3 in the power factor should be unity. The meter is adjusted by means of a hair spring on the armature.

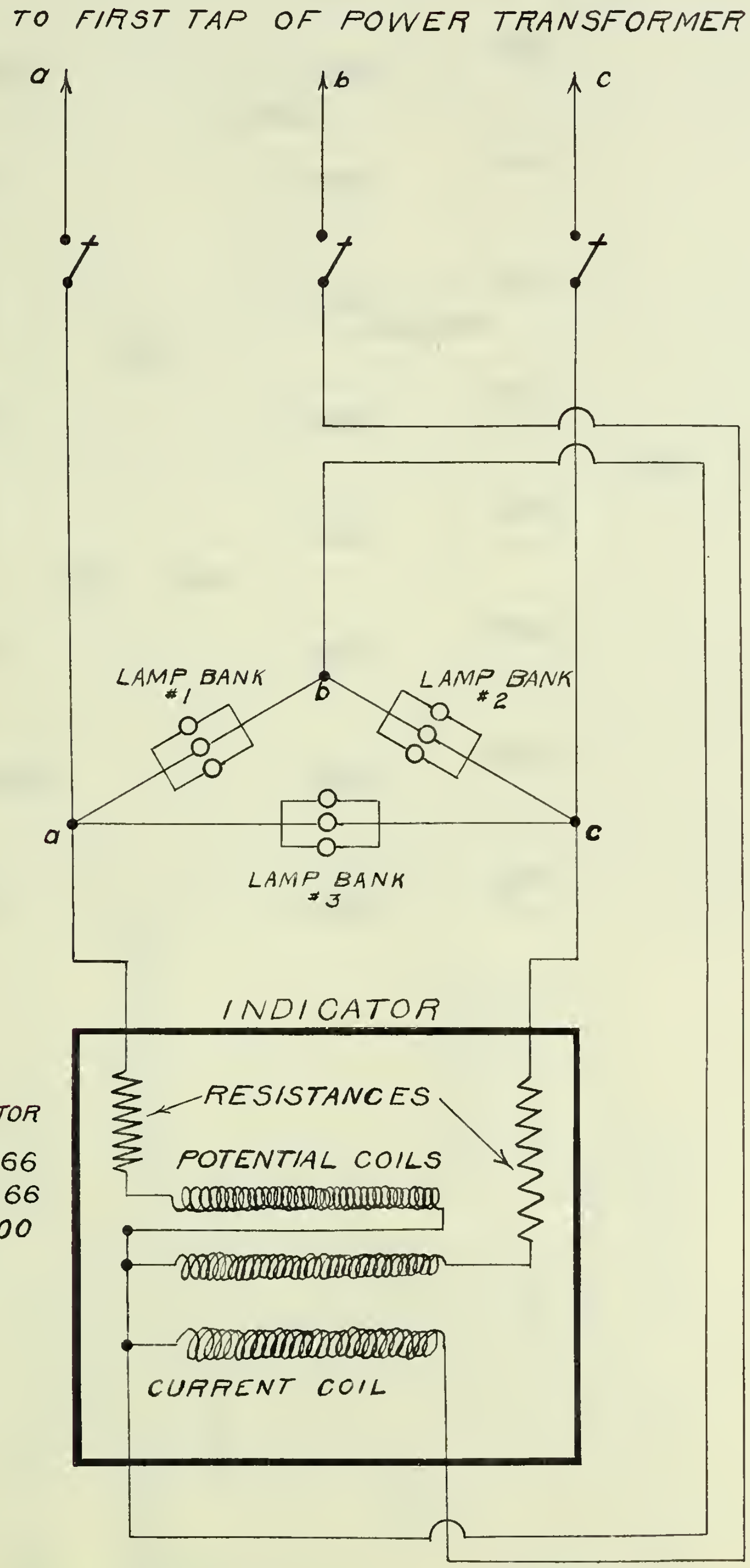
8. Speed Limit Device.

The speed limit device should be checked once a year. The method of doing this is to run the machine from the direct current side, and disconnected from the alternating current lines. The speed is increased until the point at which the speed limit coil should work is reached. This should not be greater than ten per cent of the normal speed of the machine. If the coil does not trip, the machine is shut down and by means of a set screw on the speed limit device the tension on the spring is lessened. The machine is again started and the speed increased until the point is reached where the device should operate. This is repeated until the proper

FIGURE 9

CONNECTIONS FOR TESTING

POWER FACTOR INDICATOR

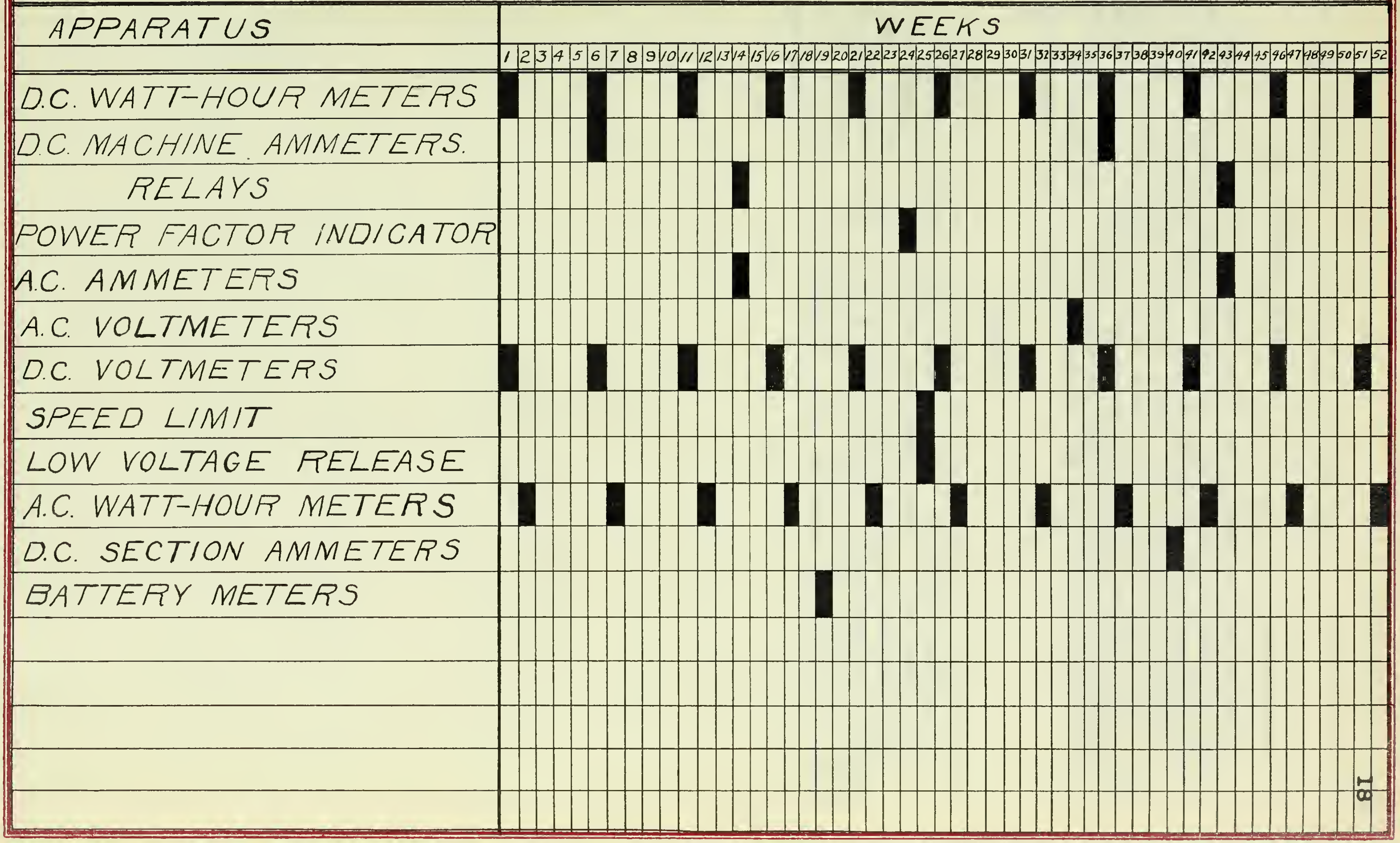


LAMPS — POWER FACTOR

#1 OUT = .866
#2 OUT = .866
#1, 2 AND 3 IN = 1.000

TESTING SCHEDULE
FOR APPARATUS IN BROAD ST. STATION

FIGURE 10



adjustment is secured.

9. Low Voltage Release.

The low voltage release coil is a part of the direct current circuit breaker (see figure 7). This can be checked when the machine is being shut down. The machine is disconnected from the direct and alternating current lines but the field switch is kept closed. As the machine slows down the voltage falls off. If the voltmeter plug is kept in the receptacle, the voltage at which the low voltage release coil operates can be read on the machine voltmeter. By means of a set screw on the coil (see figure 7) any desired adjustment can be had.

Summary.

Figure 10 shows a schedule for the testing of sub-station apparatus. Direct current watt-hour meters, ammeters and voltmeters are scheduled to be tested the same week. The reason for this is that the same apparatus can be used and all three meters checked at the same time. The same is true of alternating current ammeters and relays. The importance of these tests cannot be overestimated, and they are of greater value if made according to some definite schedule.

V. DISTRIBUTION OF POWER

The first step in the design of the power distribution system for a street railway is to make the calculations for the positive feeders. The basis for these calculations are outlined below:

Potential of the D. C. bus bar ---------------	600 volts.
Current per car (double truck, 26 tons) -------	75 amperes.
Average maximum drop in positive feeders -----	50 volts.

Outline of Feeder Calculation.

1. By means of the spot map (Fig. 1), the number of cars on each section is found at the time of maximum traffic.

2. The total load on each section is found by multiplying the number of cars on the section by the current taken by each car (Fig. 2).

3. The location of the sub-station is decided upon as described in one of the foregoing sections.

4. The cable routes are determined and drawn on the section map (Fig. 11).

5. The length of each feeder cable is now found by measuring the distance from the station bus bar to the center of the trolley section.

6. Knowing the load in amperes, the length in feet, the overall drop, and the resistances and carrying capacities of various sizes of cable, the proper size of cable is calculated for each feeder. In most cases the largest cable used is 1,000,000 C. M. If this is not large enough to carry the load another cable is placed in parallel with it.

Tie-sections.

In order to take care of emergency cases, such as station shut-downs or feeder trouble, it is well to have a number of the more important sections fed from two or more sub-stations. These sections are called "tie-sections" to distinguish them from "isolated-sections" which are fed from only one station. The "tie-sections" are so designed that, in case a station is crippled, the adjacent stations can instantly assist the crippled station and prevent an interruption of service. Figure 12 shows the locations of the sub-stations, their capacities, the load on each, and the capacities of the "tie-sections".

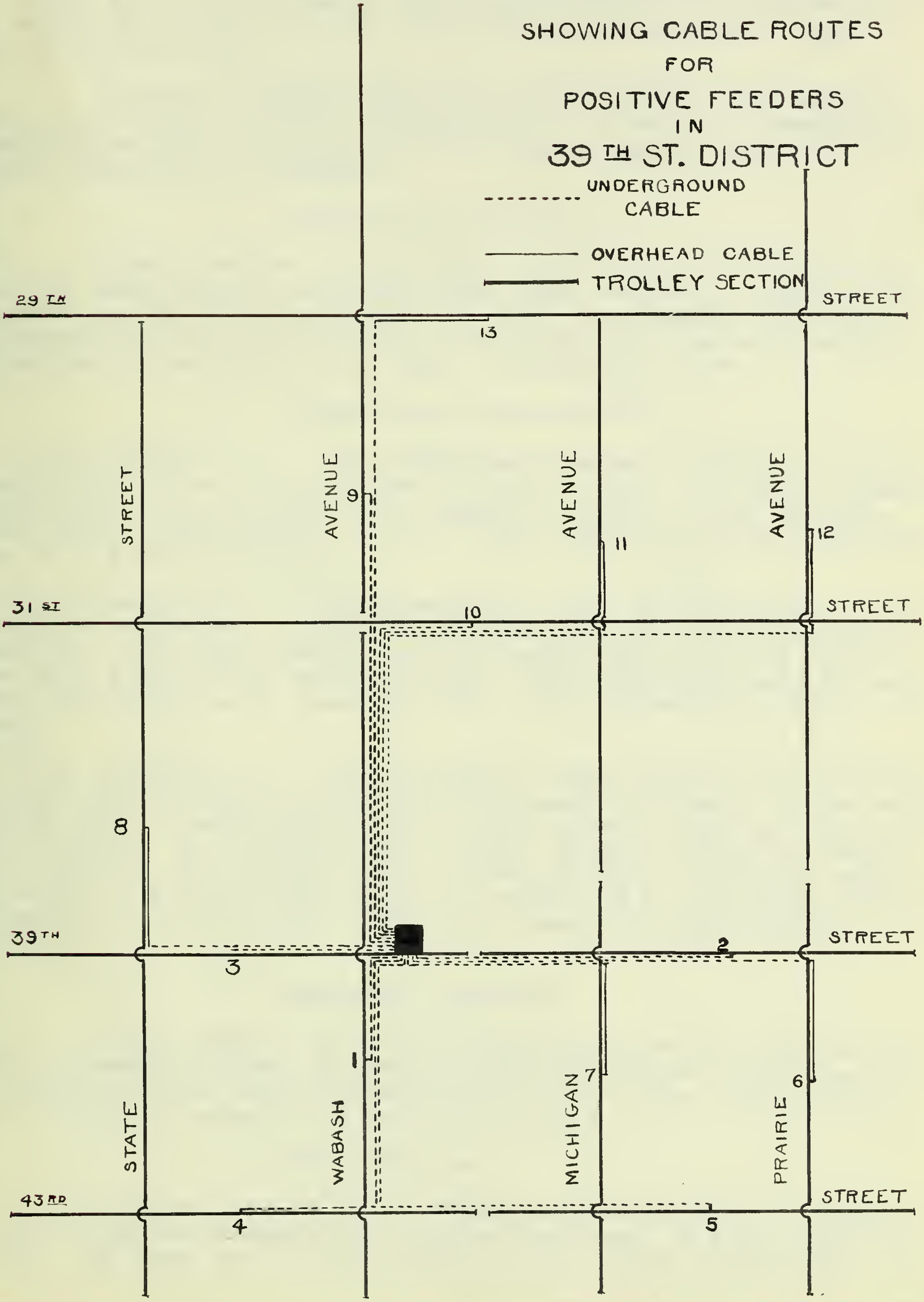
Feeder Cables.

All underground feeder cables should be lead covered. The

FIGURE 11

SECTION MAP

SHOWING CABLE ROUTES FOR POSITIVE FEEDERS IN 39TH ST. DISTRICT



insulation may be rubber, paper, or varnished cambric. The paper insulated cable is cheaper than either the rubber or cambric, and will give just about as good service. The cable should be thoroughly tested before being used. This should be done in the factory, a potential of 10,000 to 12,000 volts, alternating current being applied to the cable.

Overhead feeders should be triple-braided weatherproof cables, and should be able to withstand a variation of temperature from zero degrees to one hundred and eighty degrees Fahrenheit, without cracking or dripping.

Overhead Construction.

Where feeders are overhead, they are usually carried on steel or iron poles with wooden cross arms and pins. The line insulators are of glass, porcelain or other composition. The method of connecting the feeder cable to the trolley is the same as for underground construction, and will be described below.

Underground Construction.

(a) Conduits. -- The underground feeders are run in conduits. These conduits are of tile, cement, iron or wood. The most common material is tile, although some companies prefer cement or creosoted wood. Iron conduits are not being installed to any great extent at the present time.

(b) Manholes. -- About every 350 feet in the conduit line, a manhole is placed. These manholes are made of either brick or concrete. The brick manholes are the more common and are usually made with a reinforced concrete roof. The covers are made of cast iron. The floor is of concrete with a tile connection to the sewer.

(c) Laterals. -- Connections are made between the overhead trolley and the underground feeders by means of lateral cables which are run from a manhole through a lateral pipe or duct to the overhead conductor on the pole. The lateral pipes or ducts are made of tile or iron. The lateral cable is lead covered, rubber or paper insulated, and usually not larger than 350,000 C. M. These laterals are placed from 350 to 650 feet apart, depending upon the car traffic.

Lightning Arresters.

Some companies place lightning arresters on each feed tap. They are usually placed in a wooden box 12 feet above the ground. In addition to the lightning arresters on the poles, each section has a lightning arrester in the sub-station.

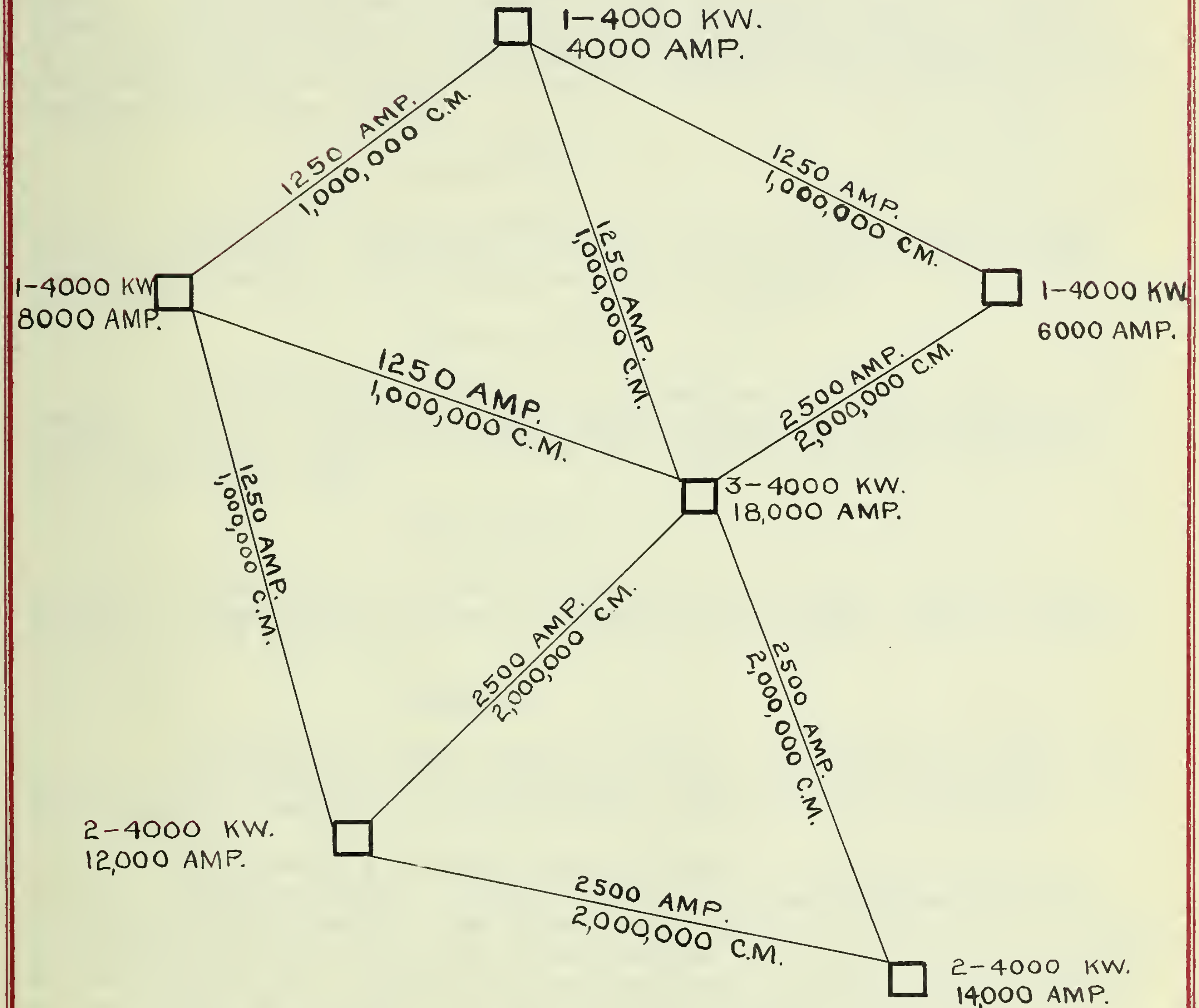
Knife Switches.

In some cases a knife switch is inserted in the lateral. The knife switch is placed in a wooden box about 12 feet above the ground. By means of the knife switch, the lateral can be dis-

FIGURE 12

TIE SECTIONS

MAP SHOWING SIZE AND CAPACITY OF TIE LINES, NUMBER AND CAPACITY OF UNITS IN EACH STATION, AND THE MAXIMUM LOAD ON EACH SUB-STATION.



connected from the trolley. This is very convenient in case of cable trouble.

Feed Spans.

A 4/0 weatherproof cable is used to make the connection between the knife switch and the trolley wire. This cable takes the place of the ordinary suspension span. The connection to the trolley is made by means of feeder ears clamped to the feeder span.

Poles.

Most cities require the use of steel poles for trolley wires. They are usually about 30 feet in height and set about 5 feet in a foundation of concrete. The pole most commonly used is a three section tubular steel pole, although some companies are using various kinds of plate box poles. Poles are placed about one hundred (100) feet apart.

Insulators.

The most common form of trolley insulator is the wood strain insulator. The usual practice is to install two of these insulators between the trolley wire and the pole.

Trolley Wire.

Trolley wire should not be smaller than No. 2/0 (B. & S. Gauge). It may be made of hard-drawn copper, phosphor bronz or silicon bronz. The trolley wires are usually suspended about 20 feet above the rails.

Span Wires.

Span wires are usually made of galvanized iron or steel except at feeder taps where the weatherproof copper cable is used in place of a span wire.

Summary.

Figure 13 shows a typical form of construction where the feeder cables are placed underground. The general arrangement of the apparatus described above is shown here.

The basis for feeder calculations, as described above, are D. C. bus potential, current per car and average maximum drop in the positive feeders. Many engineers prefer to base their feeder calculation on Kelvin's Law. This method will give the most economical design, but this is not as important in the case of feeders as the question of service. The design outlined above puts service before economy. It may be well, however, especially on small systems, to calculate the feeders by means of Kelvin's Law. This method will be described in detail later.

Great care should be used to insure the uninterrupted supply of power. The entire distribution system should be designed

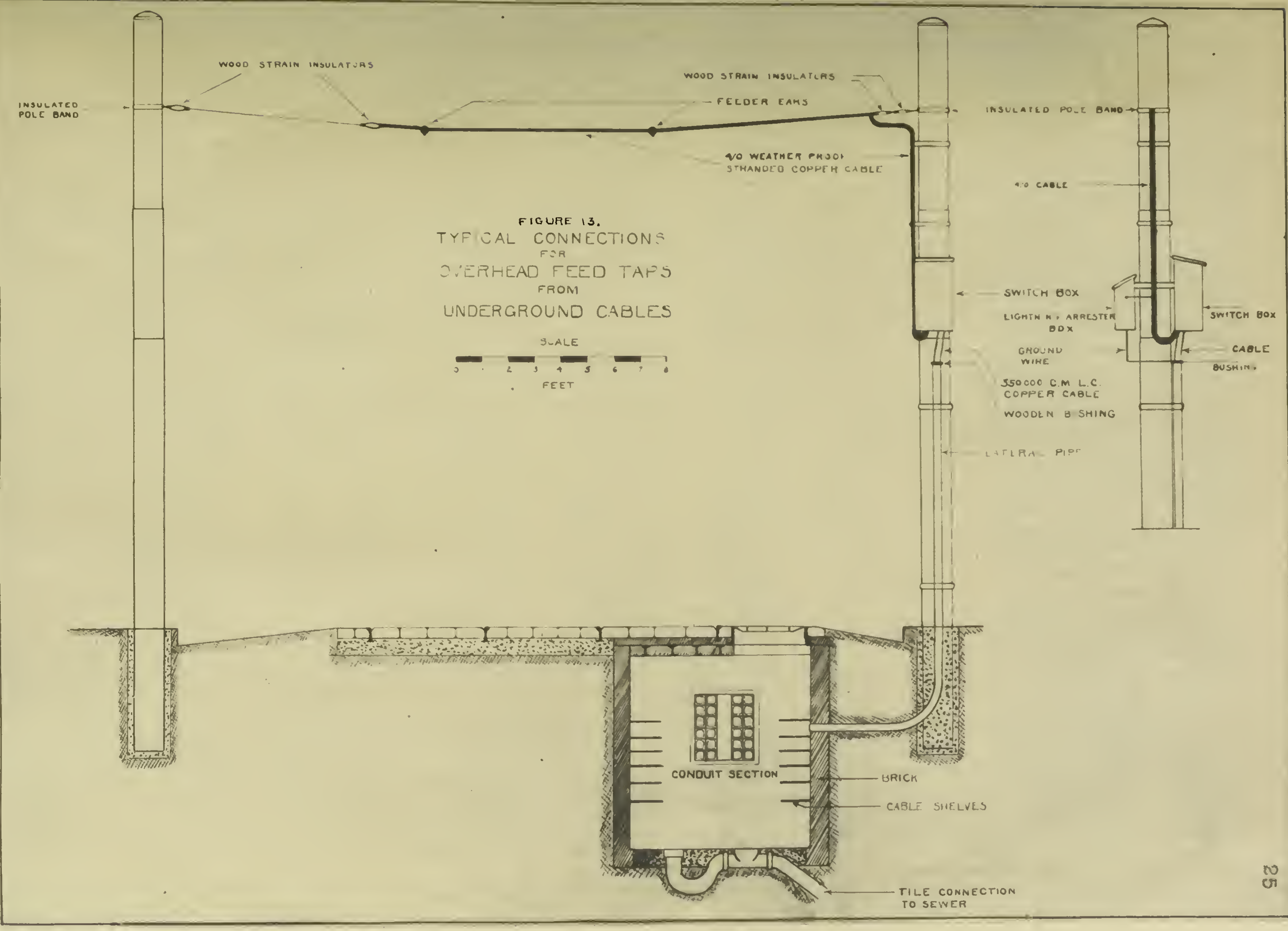


FIGURE 13.
TYPICAL CONNECTIONS FOR OVERHEAD FEED TAPS FROM UNDERGROUND CABLES

with this thought in mind. Each sub-station should be connected to the adjacent sub-stations by means of tie-feeders. On large systems these feeders should be large enough to allow several units to be shut down without interrupting the service. The use of tie-feeders makes it possible to operate with a minimum number of reserve units. If one unit of a two unit station becomes disabled, all of the tie-sections can be dropped and leave only the isolated sections to be fed by the crippled station. The remaining load is divided among the sub-stations which are connected by the tie-sections. If it becomes necessary to shut down the entire sub-station, the tie-feeders should be large enough to carry a large part of the load of the station.

VI. ELECTROLYSIS

The usual method of connecting the positive terminal of the railway generator to the trolley and the negative to the rails gives a circuit as shown in figure 14. The general path of the current is from the generator to the car, by means of the positive feeders and trolley. The return to the generator is through the rail, ground and auxiliary negative copper. The result of using the rail, in contact with the ground, as a return, is that a certain amount of current is picked up by the various under-ground metallic structures. The current is carried by these structures until a point is reached where the structure becomes higher in potential than the surrounding ground. When this point, which is usually near the source of power, is reached, the current leaks through the ground destroying the structure as it leaves it.

The amount of current leaking from the rails to the ground and underground metallic structures depends upon the following factors:

1. Electric Railway Roadbed. -- When the roadbed is made of rock or concrete and is well drained, there is offered a much higher resistance to the leakage of current than when the roadbed retains a considerable amount of moisture.

2. Bonding Tracks. -- The current flowing in the rails and that returning to the power house or sub-station by other paths are proportional to the conductances of the paths. If the rails are well bonded, the conductance of the rails will be high as compared to the conductance of other paths, and the leakage current will be small.

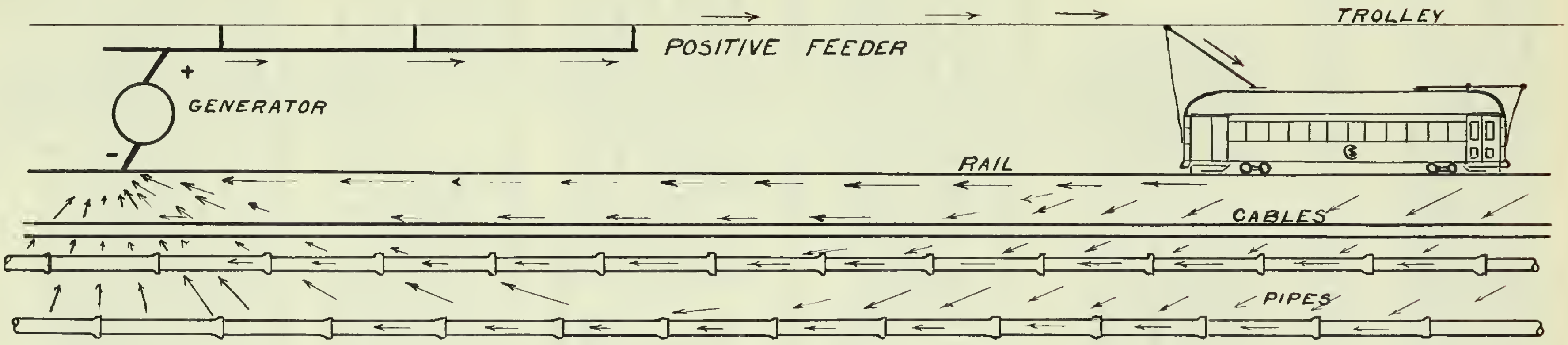
3. Soil Resistance. -- The resistance of the soil is an important factor in determining the amount of current which will be carried by the pipes, cable sheaths, tubes, etc. The specific resistance of soils varies so much with the amount of moisture, temperature, etc., that it is hard to arrive at any reliable figures on this point.

4. Contact Resistance. -- The contact resistance is mainly caused by polarization at the surface of the metal. In a short time after the current begins to flow, polarization will set in. A film resistance will be developed which will sometimes be equivalent to the resistance of ten or twenty feet of soil.

5. Overall Potential. -- According to Ohm's Law, the leakage current is equal to the voltage divided by the resistance, where the voltage is the overall potential from the sub-station, and the resistance is the resistance of the leakage path. The overall potential is determined by the size of rails and auxiliary copper, kind of bonding and current load on the rails.

Several of the above factors are beyond the power of the engineer to change without prohibitive expense. The resistance of the soil and contact resistance cannot be changed, but in some

FIGURE 14.



ELECTRIC CIRCUIT
FOR
STREET RAILWAY SYSTEM
WITH GROUNDED RETURN

ARROWS INDICATE DIRECTION OF CURRENT FLOW

cases the roadbed can be maintained in such a way as to materially cut down leakage current. This is especially true on elevated structures, in subways, and on private right of way. The overall potential is the most important factor and the one by which the municipal authorities invariably try to solve the whole electrolysis problem.

The principal methods of eliminating electrolysis are as follows:

1. Insulated coverings on underground structures.
2. Insulated joints in underground structures.
3. Drainage of underground structures.
4. Insulated track drainage (Insulated Return System).
5. Three wire system of distribution.
6. Double trolley system of distribution.

Insulated Coverings on Underground Structures.

Insulating underground structures consists of painting or otherwise covering with papers or textiles the structures likely to be damaged by stray currents. It has been definitely proved that these coverings do not prevent electrolytic action, and in some cases their presence has actually done harm.

Insulated Joints in Underground Structures.

Insulating joints in underground structures are nonconductors placed in the pipe line or cable run in such a way as to make the circuit discontinuous. As a first step in the solution of an electrolysis problem this method is not to be thought of. But, after the potential gradients on the rails have been reduced to a low value, the installation of insulating joints may eliminate any residual electrolysis on the system.

Drainage of Underground Structures.

Drainage of underground structures is a system of electrolysis mitigation in which insulated cables are run out from the negative bus bar in the sub-station and connected to the structure to be drained. The current which has leaked from the rails to the structure is removed by this cable without injury to the structure.

The first step in the design of a pipe drainage system is to make a potential survey of the sub-station district, taking readings of potentials between pipes and rails. The results of such a survey are shown in figure 15. Near the sub-station the pipes are found to be positive to the rails. This is known as the positive area. At some distance from the station the rails become positive to the pipes and this territory is called the negative area. The main object of the drainage system is to eliminate the positive area, or the area in which the current is leaking from the pipes to the rails.

From a study of the arrangement of the water and gas

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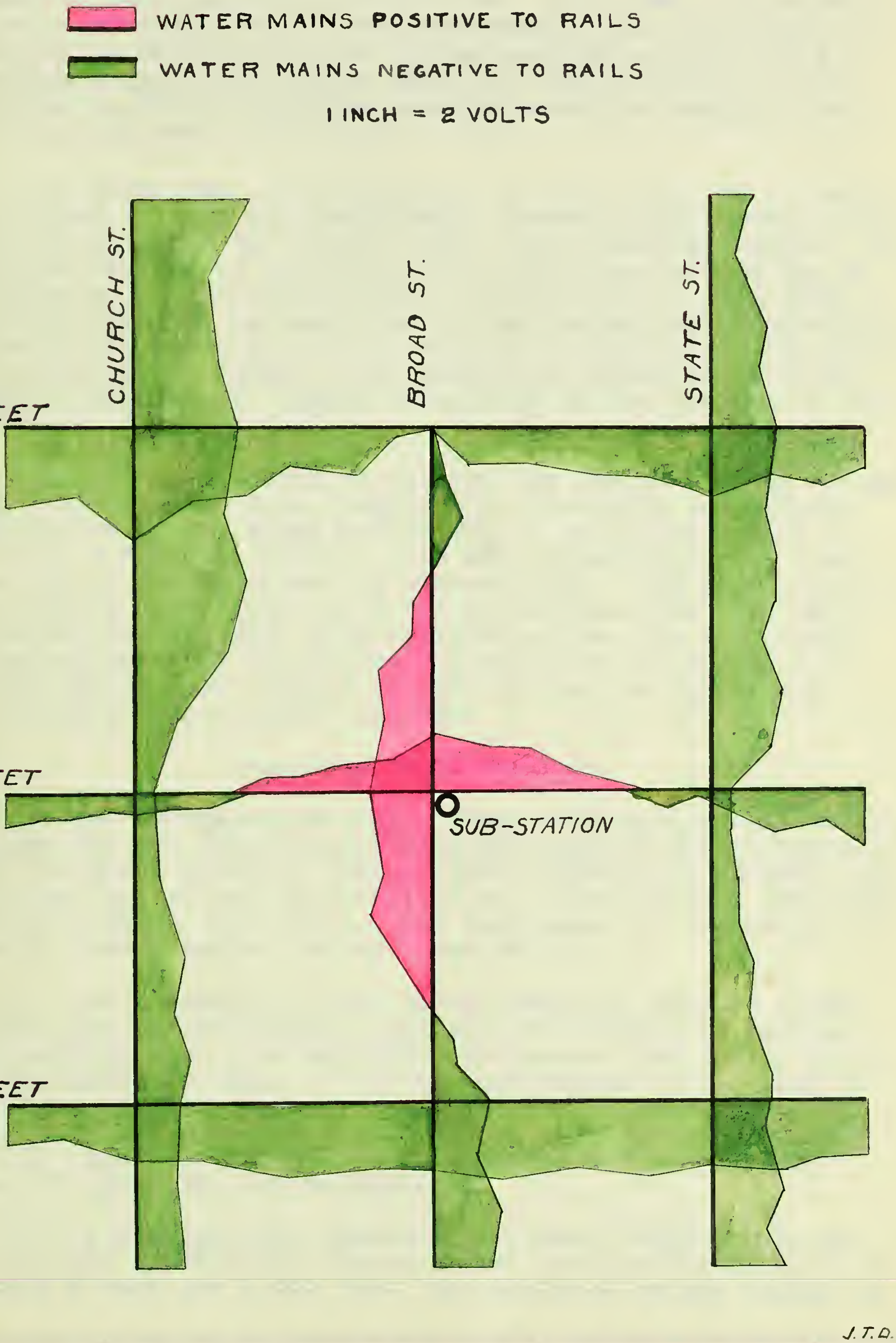
FIGURE 15.

POTENTIAL SURVEY
BROAD ST. DISTRICT



mains, the most desirable locations for drainage connections are chosen. It should be born in mind that the best design is secured when the current is drained directly from the largest mains to the negative bus. It may be found necessary to run out the drainage cables several blocks in order to accomplish this, but a much better system will be secured than if all the current was drained from a smaller main near the sub-station. It is well to install the system in several steps - each successive step requiring the extension of the drainage cables to new tapping points on the water and gas mains. After each step has been installed, a re-survey of the district should be made to determine whether the positive area has been eliminated or not.

The same idea is followed out in the design of a cable drainage system. There are conditions, however, which make a cable drainage system easier to install than a pipe drainage system. The railway cable centers at the sub-station, and the sheaths can be easily connected to the negative bus in the station. The other cable sheaths can then be equalized to the railway cable sheaths at various points where they are found to be positive to the ground or other structures. Proper fuses should be installed in these equalizers to prevent any damage being done by the failure of the railway cables.

The drainage system eliminates the positive areas of the pipes and cable sheaths with reference to the rails and ground. The current flow on the pipes and cables is increased by the installation of a drainage system. The main disadvantage of the system is due to this increase in current flow. The pipe lines are not electrically continuous, as are the cable sheaths, but have, at each joint, considerably more resistance than the continuous pipe. The opponents of the system contend that increasing the current flow will cause current to leak around the joints and destroy the pipe lengths near the ends.

Insulated Track Drainage.

In the insulated return or track drainage system, insulated feeders are run from the sub-station negative bus to various points on the track network. These feeders drain the current from the tracks and prevent an accumulation of current with a resultant excessive gradient on the rails. The main steps in the design of an insulated return system are outlined below.

1. From readings taken on all sections carried by the sub-station, the maximum ampere load on each section is secured. If these readings cannot be secured, the ampere load can be found by using the spot map (Fig. 1) in the same way as it was used in figuring the positive feeders.

2. Sizes of auxiliary copper cable and the copper equivalent of the rails are tabulated.

3. A maximum rail gradient is fixed. This should be about 1 volt per 1,000 feet. Wherever the gradient is found to be greater than 1 volt per 1,000 feet, an insulated return feeder is

installed, or additional auxiliary cable placed in parallel with the track. Auxiliary copper should not be installed in any large amounts because with a drop of only 1 volt per 1,000 feet, the copper will not be worked at a very high efficiency. It is desirable to make the taps to the rails at intersections which have more than one direct path to the sub-station.

4. When the locations of the negative feeder taps have been chosen, a tabulation is made of miles to sub-station, size of cable, resistance and average ampere load. In this way the drop on the rail and cable is secured. The load in the cable and track is adjusted until the drops from any intersection over its various paths to the sub-station are equal.

5. In order to have the cables which tap the rails at the outlying points take their proportion of the load, it is necessary either to install negative boosters in series with these, or, better still, to insert resistance in series with the cables which tap the rails near the sub-station. There is no way of determining off hand the amount of resistance to be placed in series with these cables. Three estimates should be made, using 10, 15 and 20 volts drop between the negative bus and the nearest cable tap. The value which gives the most economical installation, as explained below, is used in the design of the system.

6. The size of cable required for the return feeders is found by means of the following formula:

$$S = K \frac{I \times L}{E}$$

S = size in circular mills.
I = current in amperes.
L = the length in miles.
K = the resistance per mile of 1 circular mill.
E = the determined drop over the cable.

7. The line loss at any time is equal to the current squared times the resistance. The average line loss is, therefore, equal to the mean of the currents squared times the average resistance of the return. In practice the line loss is found by using the formula

$$L.L. = \sqrt{\text{mean } I^2} \times E.$$

E is the voltage drop from the section to the sub-station. The

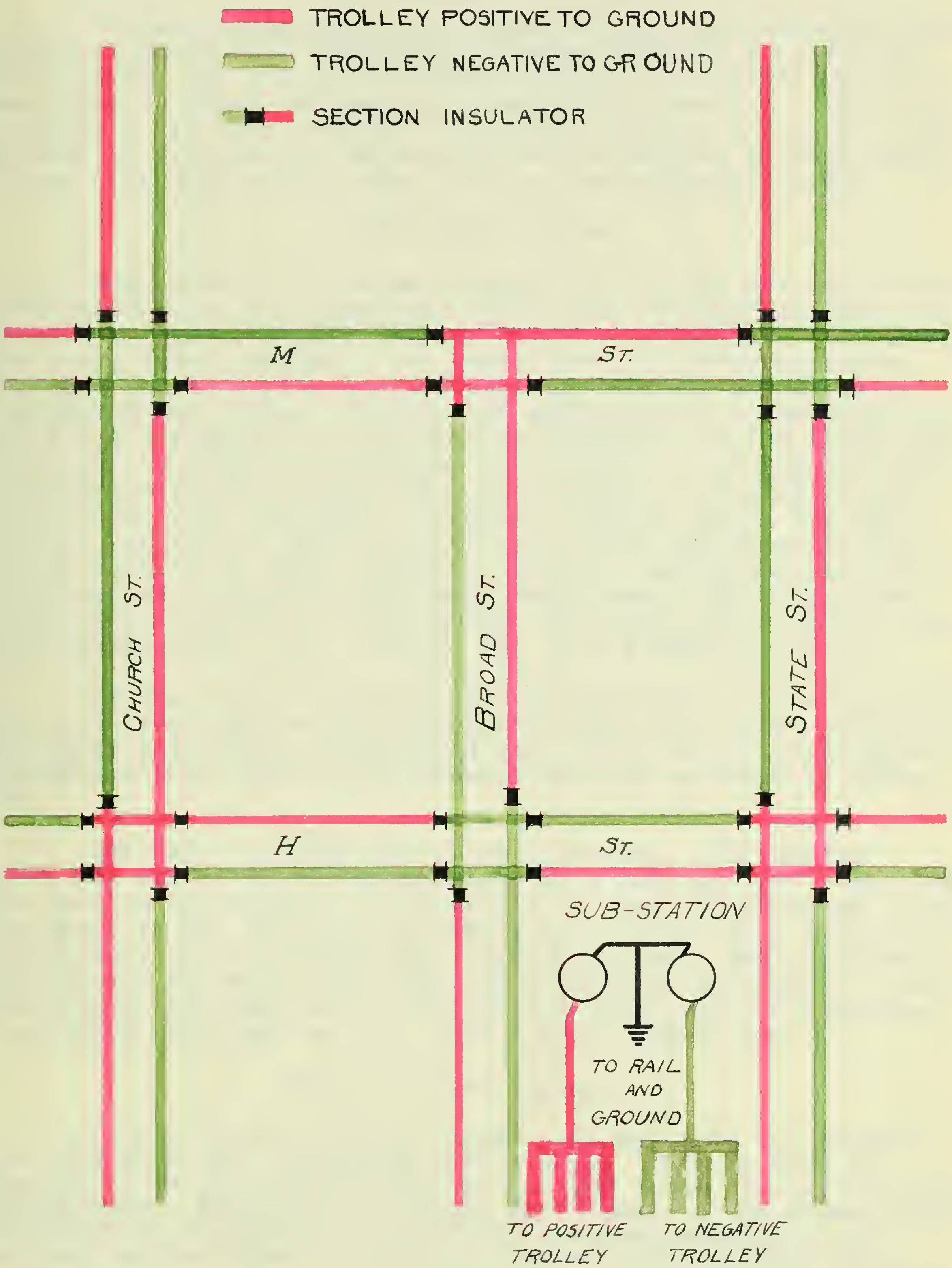
$$\sqrt{\text{mean } I^2}$$

is found by getting ampere readings with a curve drawing meter on each section over a twenty-four period, squaring each reading, averaging the squares and extracting the square root of the average.

8. The total cost of the installation is found by tabulating the costs of cable, conduit, poles, resistances, welding, paving, panels, instruments, etc.

FIGURE 16

TROLLEY SECTIONS FOR THREE WIRE DISTRIBUTION SYSTEM



9. The cost of line losses is balanced against the fixed charges --- interest, taxes, and depreciation on the cost of installation. The most economical installation is secured, according to Kelvin's Law, when the annual line losses equal the annual fixed charges and as a result the total cost is a minimum.

The installation of the track drainage system lowers the potential of pipes with reference to rails, both in positive and negative areas, but the positive area is not eliminated. The current flow on pipes and cables is materially reduced. The overall gradients are also reduced. The main disadvantage is the cost. The system is very costly to install and introduces an additional operating cost due to the power loss in the resistance grids.

Three Wire System.

The three wire system of distribution has not been given the attention which the insulated return and drainage systems have received. In many respects, it has distinct advantages over either of the above named systems. Two generators or synchronous converters are run in series and the neutral terminal is connected to the ground and rails. The trolley sections are so arranged that one-half are connected to the positive terminal and the other half to the negative terminal, as shown in figure 16. In figure 16, the sections are divided in such a way that, over a given half mile, the east bound cars run with a negative trolley, while the west bound cars run with a positive trolley, and in the adjacent half miles the reverse is true - namely, that the east bound cars run with a positive trolley and the west bound cars with a negative trolley. The same plan is followed on the north and south streets. At each intersection, all trolleys are at the same potential.

If the load is balanced no current flows in the rails or ground, and electrolysis is eliminated. Under the worst possible condition of unbalance, there would not be any more current flowing in the ground than there is at present with an ordinary grounded return.

The main disadvantage is in operation. The system requires the operation of two machines in a sub-station, regardless of the load on the station. The result is that the machines, during a large part of the day, are operating with a very poor load, and the efficiency of the station is, therefore, low. Another disadvantage of the system is the flashing at section insulators. The section insulators have 1200 volts across them, and a car running over one with the power on will draw a considerable arc.

Double Trolley System.

In the double trolley system, the positive and negative feeders are both kept insulated from ground. This is done by running out from the sub-station two trolley wires, either overhead or underground. There is no leakage of current to the ground, and electrolysis is absolutely eliminated. Another advantage the system has is that when a trolley or feeder gets grounded, that side of the machine can be grounded temporally, and the service will

not be interrupted.

The main disadvantage of the system is the cost. When the double trolley is installed overhead, the cost is about double the cost of a single trolley. When the double trolley is put underground, the cost is more than triple the cost of a single trolley overhead. The maintenance on the system is also more than double the maintenance on the grounded return system.

Summary.

Each of the various systems of electrolysis mitigation, as described above, has certain advantages and disadvantages. No definite statement can be made as to which system is the best. Under a given set of conditions, one system would be a success which, with a different set of conditions, would prove to be an utter failure.

Before any system is installed, a thorough study of local conditions should be made by competent engineers. A committee should be formed of representatives of the various companies interested in the electrolysis problem. A general survey should be made to determine electrolytic conditions as they exist at the present time. The survey should include potential readings between underground cables, water and gas pipes, rails and ground. Potential drops over 300 feet lengths of street car rails, water and gas mains should be taken every quarter mile. From this data, the gradients for these structures can be figured. Overall potentials from the sub-station to the distant points on the rails should be taken, using telephone wires and high resistance voltmeters. From a study of this data, the committee becomes familiar with existing conditions. In most cases the solution of the problem lies in the installation of one of two systems. It is well to prepare estimates of the costs of both these systems, and let the committee decide which will give the maximum protection for the minimum cost.

VII. CONCLUSION

For the last ten years, the development in the generation and distribution of electric power for street railways has been toward shorter direct current feeding distances and smaller simplified sub-stations. In this connection, it might be well to say a word about the automatic sub-stations. These stations are being used to some extent on interurban lines but have not, as yet, come into general use on large street railway systems. On the latter systems, there would be a saving of operators salaries, but in the case of the interurban systems the sub-station operates only when a car is on a section fed by that station and, therefore a considerable saving in power is effected in addition to the saving in operators salaries. There is a great field for experiment and development along this line, and it may be that the next ten years will see the automatic, semi-automatic, or remote control sub-station replacing the present manually operated stations to a great extent.

In the automatic sub-stations, the machines start and stop automatically. When the trolley voltage drops below a certain fixed value, the rotary automatically starts and is thrown in on the direct current lines. The rotary continues to operate until the load drops off, and it then automatically disconnects from the direct and alternating current lines and comes to rest.

In the semi-automatic sub-stations, an operator is required to start and stop the machines, but the station is supplied with protective devices so that, if any trouble occurs, the machine will not be damaged but will be disconnected from the direct and alternating current lines. The direct current feeders are equipped with automatic reclosing circuit breakers to take care of overloads on the feeder sections. One operator can take care of several of these stations.

The remote control sub-stations are operated from another sub-station or from a load dispatcher's board at some central point. In this way many new sub-stations can be added to a system without increasing the present operating force.

Whether the sub-station is an automatic, semi-automatic, remote control, or manually operated, it should be properly located and carefully designed. All unnecessary apparatus should be eliminated. The sub-station building should be well ventilated, light and large enough to accommodate the apparatus without crowding.

Frequent tests of sub-station apparatus should be made. In doing this, it is well to follow some definite schedule such as outlined in figure 10.

The distribution system should be carefully designed and well constructed. The very best of materials should be used. Adequate provision should be made to take care of overloads on the system. Tie-sections should be installed so that in case a sub-station is crippled it can be assisted by the adjacent stations.

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Each sub-station should have sufficient capacity to take care of its load without overloading the machines. There are, however, times when it becomes necessary to overload a station, but this condition should not last longer than thirty minutes, and the overload should not be greater than fifty per cent of the rated capacity of the station. The system, as a whole, should have some reserve capacity. On large systems, this reserve capacity should be sufficient to allow the shutting down of at least ten per cent of the machines at any time without putting an overload on the machines in service. This reserve capacity should be well distributed over the system so as to give the maximum protection against shut-downs.

In the preceding section the electrolysis question was discussed and the principal systems of mitigation described. The first step in the solution of any electrolysis problem is to secure the cooperation of the various companies interested in the problem. A committee should be formed of engineers representing these companies, and the final solution of the entire problem should be left to this committee.